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SIMPLE FIELD-OF-VIEW CALIBRATION PROCEDURE FOR HIGH FIDELITY PHOTOGRAMMETRY

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This report introduces a simple and straightforward field-of-view calibration procedure for fixed-view cameras to be used for U.S. Army weapon's testing. This method will significantly improve the accuracy of photogrammetric measurements for both two-dimensional and three-dimensional (3D) applications by correcting for image skew and large-scale, non-spherical image distortions. The process makes use of a sub-pixel reference point selection technique in camera images, and precision surveyed points in 3D, allowing a more accurate affine transform to be generated between image coordinates and their projection onto a calibration plane in 3D coordinates. Although not necessary, the process can be made even more accurate by first conducting a conventional camera/lens calibration procedure to account for spherical aberrations. Given the simplicity of this approach and the advantages it provides, it is recommended to use this procedure at all U.S. Army tests where high-fidelity measurements are required from video collected with fixed-view cameras systems.

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INTRODUCTION

Camera systems provide a wealth of useful information for evaluating military field tests. Methods that extract this information (like photogrammetric analysis) from photographs, standard videos, and high-speed videos are commonly used for a variety of U.S. Army development efforts. In most cases of photogrammetric analysis, U.S. Army personnel believe cameras are the perfect instruments to provide flawless images of the real world. Obviously, this is not the case. Camera lenses have flaws. Pixels in a digital image are not actually square. For some basic conditions (such as determining when an observable event occurred in a video), corrections to camera errors are not required. However, distortion errors must be addressed when accurate measurements of angles or relative distances are required.

If conducted without any camera distortion corrections, photogrammetric analyses may still have substantial errors. The method discussed in this report can be used in numerous applications for both military and non-military purposes. If the video is used to obtain accurate measurements, then this approach works well in military field tests where video is collected using fixed-view cameras [or the camera and field-of-view (FoV) does not change during the video]. Measuring distances in a two-dimensional (2D) plane (such as estimating the miss distance from a target or characterizing weapon recoil motion) is another area that would benefit immensely from this approach. With the proposed calibration method discussed in this report, the techniques used to obtain results in advanced three-dimensional (3D) analysis (such as recreating a bullet's trajectory) also become much easier and more accurate.

THE DIFFICULTY OF CONVENTIONAL IMAGE CORRECTION

There are several approaches for correcting distortions in camera/lens systems. The most accurate methods involve performing a complete camera/lens FoV calibration, as discussed in references 1 and 2. The conventional approach discussed in this report is called "Complete Camera/Lens System Calibration." This approach can be used to correct problems caused by camera skew, spherical aberrations, and some local aberrations of the camera/lens system. Figure 1 shows sample images of video frames from conventional analyses.

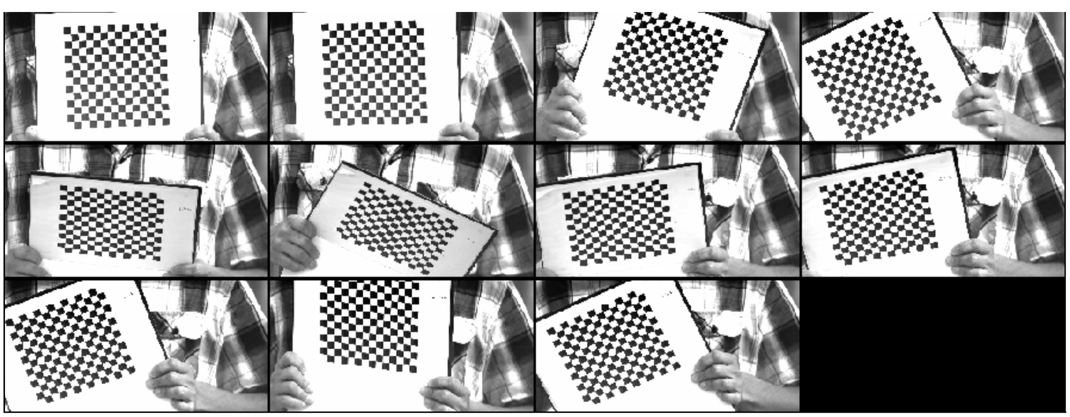

Figure 1
Sample images using conventional "Complete Camera/Lens System Calibration"

Unfortunately, there are problems with this approach that can make munitions testing difficult. The first problem is that setting up the resources for collecting calibration video (or a set of still photographs) often takes a significant amount of time. At most large-scale U.S. Army artillery tests (up to 100 personnel may be present), there are several camera personnel required to operate multiple cameras recording the calibration video. These cameras cannot be set up in their final positions (orientation and focus) until all weapons, targets, and other test equipment are set up in their final positions. Waiting until all cameras are in their final positions often means delaying a test for personnel who are already set up to run the test.

Another problem is that a single set of calibration images is specific to one zoom and focus level. Once the final settings are achieved, some camera operators apply masking tape to adjustable-focus lenses to ensure the camera's focus does not change during the test. However, many sophisticated camera systems perform internal autofocus operations when camera power is interrupted or the test sequence is paused for the night. This action invalidates the calibration settings.

Both problems together are costly and prohibit the creation of realistic schedules for most large-scale tests when performing a complete camera/lens system calibration. Essentially, these type of calibrations work well for highly-controlled laboratory test setups and probably won't work for fast-paced outdoor tests. Fortunately, the simple matrix algebra method discussed later in this report can be used with or without a conventional camera/lens calibration.

CONVENTIONAL APPROACH TO PHOTOGRAMMETRIC ANALYSIS

Photogrammetric analysis of test video is normally conducted by U.S. Army personnel manually. They take measurements on individual video frames by selecting various pixel locations and then recording the X and Y pixel coordinates of the desired points. To translate the X and Y image pixel coordinates into useful units of distance, select a reference object of known length. For example, the height of the target (or reference length object) shown in figure 2 is 20 ft. This same distance is roughly 375 pixel rows. During testing, an object impacts the target shown in figure 2. The offsets for the impact point is 110 pixels horizontally and 120 pixels vertically from the target crosshairs. The miss distance according to the simple manual analysis used in equations 1 and 2 is:

$$\Delta Y = \frac{120\,pixels}{375\,pixels} * 20ft = 6.40ft \tag{1}$$

$$\Delta X = \frac{110\,pixels}{375\,pixels} * 20ft = 5.87ft \tag{2}$$

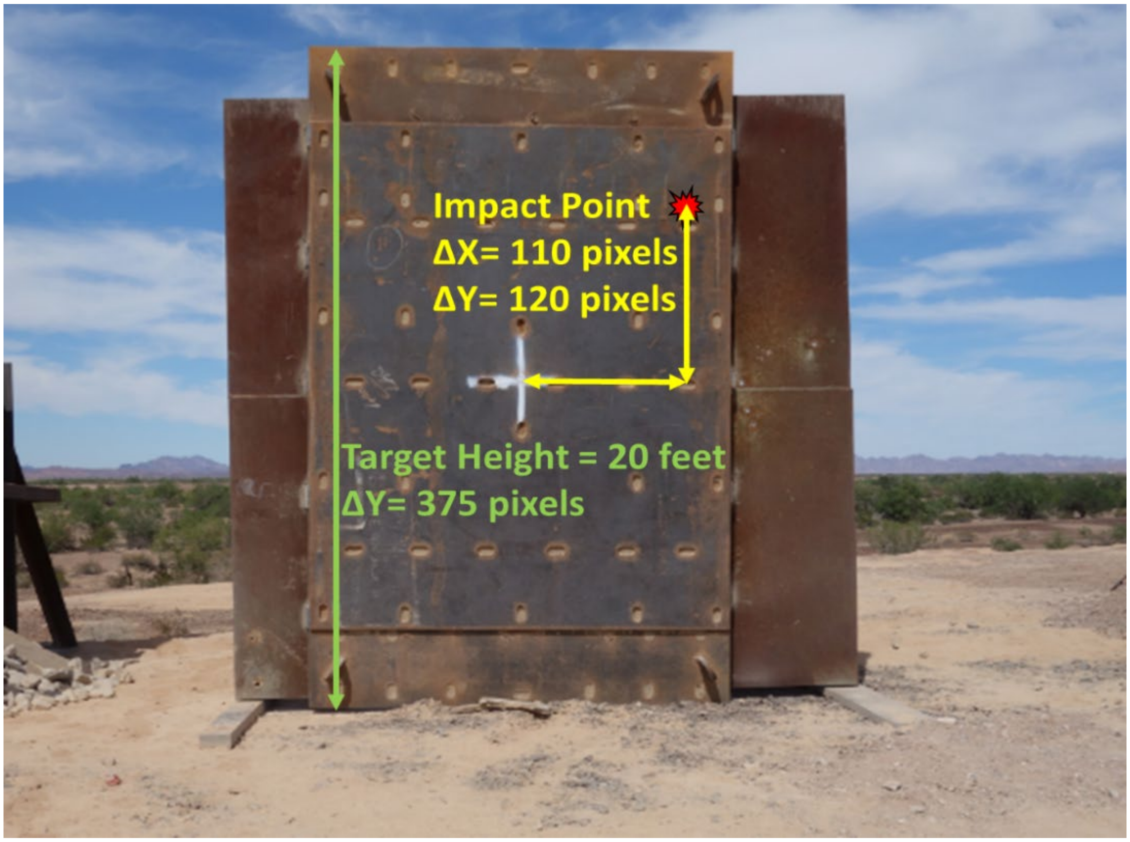

Figure 2
Example of reference length distance measurement

Several problems exist with this simple approach. First, the analysis in equation 2 assumes pixels are square or the ratio of feet-per-pixel is the same for both the X and Y directions. In practice, this is rarely true. The skew value between the horizontal and vertical directions can vary by several percentage points for high-speed cameras with precision lenses costing over $100,000. Correcting image skew is extremely important when using pixels to measure angles in an image.

A second problem with this analysis is that it appears the impact plane is closer to the camera than the back of the 20-ft target face. It is critical to ensure that the reference length object is the same distance from the camera as the object being measured. A third problem is that it appears the camera was not perpendicular to the target face or that the height of a pixel at the top of the target face is not the same as the height of a pixel at the bottom of the target face. The correct approach for adjusting camera distance and perpendicularity is discussed later in this report.

In this type of simplistic photogrammetry, the reference length object should be as large as possible and still fit the FoV since the “off by one” pixel error grows if the reference object is small. For example, if the 70-pixel height of the white crosshairs (painted on the target) is used as the reference length, the result is a length conversion precision of 3.43 in. instead of 0.64 in. (using the total target height).

Semi-automated photogrammetric analyses are also conducted by the U.S. Army. A variety of third-party software applications exist to aid in the test video data reduction analysis. These software packages often have their own recommended calibration procedures.

SIMPLE MATRIX ALGEBRA METHOD FOR ACCURATE MEASUREMENTS

This section describes the simple matrix algebra method for resolving issues with camera/lens system calibration for a variety of applications. When used in conjunction with the complete camera/lens system calibration described in a previous section, this method should still be used to further increase the accuracy of measurements. In cases where a complete camera/lens system calibration is not practical, it also does an excellent job of correcting large-scale aberrations and image skew errors (largest contributors of errors for most range camera setups). Without a complete camera/lens calibration, this approach does not account for spherical or local lens aberrations. Inexpensive low-grade lenses and wide FoV lenses (such as fisheye lenses) tend to have increased spherical distortion. Unless high-grade tight FoV lenses are used, it is recommended that a complete camera/lens calibration always be performed.

This simple calibration method is easy to implement for large-scale military testing scenarios. It can be conducted before, during, or after a test if the on-site survey is conducted when the test equipment is in its final position. The survey can often be conducted in parallel with other test efforts and prevents tests from being slowed down to accommodate camera calibration. It can also accommodate small changes in focus or camera zoom if the reference points remain in the FoV in at least one frame of the test video or a separate segment of the test video is collected with the surveyed reference points placed in the FoV before or after the test event.

To implement this approach, a minimum of three precise reference points must be placed in the FoV, but four or five reference points are recommended. Using more points improves accuracy but adds a short amount of time for additional surveying. The placement of each reference point is important. If measurements must be made throughout the image, then there should be at least one reference point in each quadrant of the FoV. These points should be spread out in both the horizontal and vertical directions at a minimum. Having the reference points placed throughout the FoV improves precision, but aberrations tend to be greatest at the extremes of the FoV. Some engineering judgment is required to find the proper balance. Also, placing the reference points at the extremes of the FoV may increase the chance that they become cropped out if the zoom level is increased or the camera is slightly moved.

Reference points must have a sharply defined center. When reference points are spray painted as an “X” (shown in fig. 2), the center of the shape must clearly be sharp. Sharp corners, stick-on reflectors, and bow tie markers also make excellent reference points. When using blunt objects such as telephone poles, the reference point must not be the center of the pole. It should be a distinct edge or corner (with the red triangles shown in fig. 3) because the precise X and Y location of these edges can be identified.

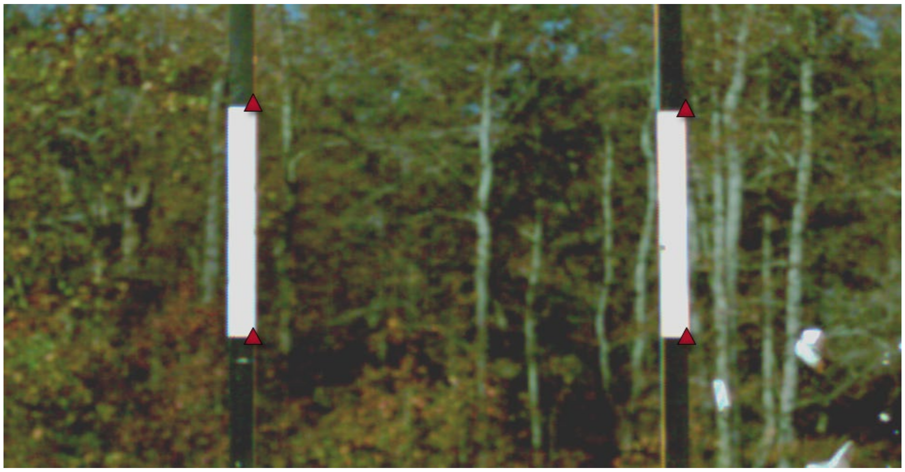

Figure 3
Use distinct edges or corners for reference points

Since a single camera image is 2D, it can only be used to make measurements in one plane. If possible, place the reference points in the plane of interest. For example, to measure an impact location on a flat target, place the reference points on the target face. If reference points must be placed in an alternate parallel plane to avoid destroying them (such as using a side-view for ammunition testing), then use the method discussed in the next section to make measurements accurately.

Once the camera is situated, reference points should be added to the FoV and surveyed. Any right-handed coordinate system will work when receiving geodetic survey coordinates, but use the Universal Transverse Mercator (UTM) coordinates to record the Easting, Northing, and Up UTM coordinates. It is recommended to first identify what data is required since some test sites do not record the Up (Z) coordinate unless it is requested. For U.S. Army munitions testing, it is often helpful to rotate on the upward axis to a coordinate system originating at the gun system and the downrange (DR) direction pointing toward a DR target using the conversion in equation 3. In this convention, the firing azimuth (Az) is measured counter-clockwise from the East in degrees, as shown in equation 4. Yuma Proving Ground (YPG), Yuma, Arizona, reports their Az ("Line of Fire") clockwise from the North in degrees. Since this is the convention used in the aviation field, the adjustment in equation 5 is required.

$$\begin{bmatrix} DR \\ CR_{(left)} \\ UP \end{bmatrix} = \begin{bmatrix} \cos(Az) & -\sin(Az) & 0 \\ \sin(Az) & \cos(Az) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} East_{UTM} - East_{Gun,UTM} \\ North_{UTM} - North_{Gun,UTM} \\ Up_{UTM} - Up_{Gun,UTM} \end{bmatrix} \tag{3}$$

Where

$$Az = \operatorname{atan}\left(\frac{North_{Target} - North_{Gun}}{East_{Target} - East_{Gun}}\right) \tag{4}$$

or

$$Az = 90 - LoF_{YPGcoords} \tag{5}$$

With the gun, target (or "Line of Fire"), and reference point coordinates surveyed, the FoV of the camera now can be calibrated for the 2D analysis in the 3D coordinates. As previously mentioned, this can be performed by using actual test video (if the reference points remain in the FoV) or a segment of calibration video (if the reference points will be removed before the test). If the reference points are removed, then the camera position, orientation, and focus must not change between the calibration video and the video that will be analyzed.

The reference points now need to be numbered. Use the following recommended convention to list the reference points for the corners in clockwise order and then add other points at the end.

1) Top left point
2) Top right point
3) Bottom right point
4) Bottom left point
5) Center point (if used)

For the calibration video or test video sequence, the X and Y pixel coordinates of the reference points must be entered into the pixel position vector in the same order. To achieve sub-pixel accuracy using a computer mouse, zoom in on each reference point as closely as possible and then record several estimates of the coordinates for the center of each reference point. Move the mouse and cursor away from the reference point several times to determine its pixel locations for your estimates. Take the average of at least five estimates for each reference point to create a robust final average of the sub-pixel X and Y coordinates. Perform this procedure across several frames of video to increase accuracy.

The next step is to determine the affine transform matrix ($M_{transform}$). If using four or more reference points, the matrix algebra will be overdetermined. Since a true inverse does not exist in this case, a generalized inverse can still be computed to solve the linear equations. The MATLAB software application automatically resolves any over-determined systems by computing the Moore-Penrose pseudoinverse in place of the inverse. The Moore-Penrose pseudoinverse of A is defined as a unique solution to the following four equations:

- AXA = A
- XAX = X
- (AX)* = AX
- (XA)* = XA

Where the asterisk represents the conjugate transpose (ref. 3).

The use of the pseudoinverse is similar to approximating a least-squares fit to equations 6 and 7 using matrix division.

$$\begin{bmatrix} DR_1 DR_2 DR_3 \cdots \\ CR_1\, CR_1\, CR_3 \cdots \\ UP_1\, UP_2\, UP_3 \cdots \\ 1 \quad 1 \quad 1 \quad 1 \end{bmatrix} = \boldsymbol{M_{transform,4x3}} \cdot \begin{bmatrix} X_1 X_2 X_3 \cdots \\ Y_1\, Y_2\, Y_3 \cdots \\ 1 \quad 1 \quad 1 \quad 1 \end{bmatrix} \tag{6}$$

Solve for $M_{transform}$,

$$\boldsymbol{M_{transform,4x3}} = \begin{bmatrix} DR_1 DR_2 DR_3 \cdots \\ CR_1\, CR_1\, CR_3 \cdots \\ UP_1\, UP_2\, UP_3 \cdots \\ 1 \quad 1 \quad 1 \quad 1 \end{bmatrix} / \begin{bmatrix} X_1 X_2 X_3 \cdots \\ Y_1\, Y_2\, Y_3 \cdots \\ 1 \;\; 1 \;\; 1 \;\; 1 \end{bmatrix} \tag{7}$$

Where the subscript numbers represents the reference point number.

This affine transform ($M_{transform}$) will now project any desired pair of image coordinates onto the 3D calibration plane. It represents a least-squares fit plane to all surveyed reference points. Use the computer vision, image processing, or manual analysis methods to generate a list of 2D X and Y image coordinates and then project them onto the 3D coordinate system, as shown in equation 8.

$$\begin{bmatrix} DR' \\ CR' \\ UP' \\ 1 \end{bmatrix} = \boldsymbol{M_{transform,4x3}} \cdot \begin{bmatrix} X' \\ Y' \\ 1 \end{bmatrix} \tag{8}$$

This approach yields much better results than conventional analysis when using reference length objects in the FoV. This is because the calibration is based on several sub-pixel reference points, precision-measured surveying, and a least-squares overdetermined transform matrix. It projects the results into the 3D coordinate system with the units already inherent in the conversion. Projecting measurements into 3D space provides additional benefits for 3D analysis (discussed in a later section).

CORRECTION FOR MEASUREMENTS NOT IN CALIBRATION PLANE

Often, the measurement often do not occur on the calibration plane. Measuring a distance or length of an object not on the calibration plane (or between the calibration plane and camera) results in an overestimate of its length. This is problematic because objects appear bigger as they approach the camera. The opposite problem exists if the object is beyond the calibration plane. To adjust for this situation, the distance of the object from the calibration plane must be known.

The distance between the plane where measurements are made (actual motion plane) and the calibration plane needs to be determined. To determine the distance of an object from the calibration plane, use the approach described in the previous section with a second camera that has an orthogonal view from the first camera. The next section in this report describes how to use two orthogonal (or quasi-orthogonal) cameras.

For munitions testing, another method is used to determine the offset from the calibration plane. This method assumes that the munition object is constrained to the plane of the firing direction. It is used often to capture a side-view of a bullet's motion by a camera. Since tests are slowed down by repeatedly installing reference points on wooden poles directly in the line of fire of a weapon system, the reference points are all positioned several feet to the far side of the Az of fire. These reference points remain in the FoV throughout the test event, as shown in figure 4.

Figure 4
Calibration markers beyond line of fire and orthogonal views

For proper correction of the calibration plane offset, the surveyed 3D coordinates of the camera system are required, and ideally, the focal length of the camera/lens system should also be known. As shown in figure 5, an object that appears between the calibration plane and the camera will project a larger shape when the transform matrix is used to convert image coordinates to 3D coordinates. This geometry allows a linear correction.

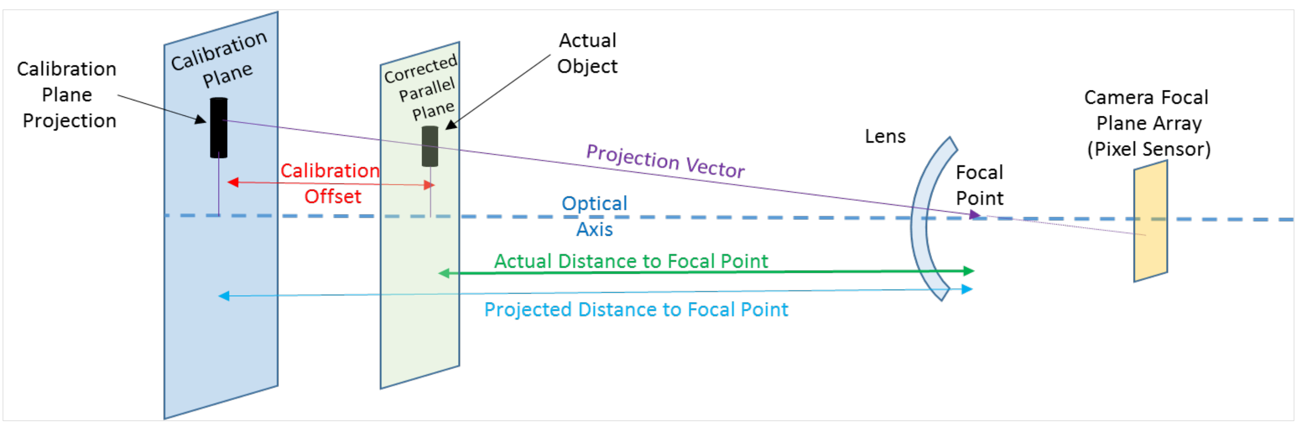

Figure 5
Focal point and projection plane diagram

To make the correction, the pin-hole camera model must be assumed, and the 3D position of the object can be corrected by projecting the 3D position into a corrected plane that is parallel to the calibration plane. This can be thought of as moving some distance along the 3D vector from the object's calibration plane coordinate toward the camera focal point. The focal point lies on the camera's optical axis at a distance of one focal length in front of the image sensor. For maximum accuracy with this correction, the actual position of the sensor and the focal length must be known.

If the camera's optical axis (or camera pointing direction) is not perpendicular to the calibration plane, then the distance of the camera in the normal direction to the calibration plane must be used for plane-offset-correction. The normal direction of the plane can be determined by projecting any three points (for example, center, top left, top right) of the image XY coordinates into 3D coordinates using the transform discussed in the previous section. Then, create two vectors by subtracting any two points in 3D from the third point in 3D. For example, vector one could be the top left point 3D coordinates minus the center point 3D coordinates and vector two would be top right point 3D coordinates minus the center point 3D coordinates. Then, the normal direction vector of the calibration plane is the cross product of those two vectors. To determine the distance of the camera's focal point along this direction (Distance "C"), measure the perpendicularity of the camera's view by using the dot product formula shown in equation 9.

$$Perpendicularity: \ \cos(\theta) = \frac{A \cdot B}{|A||B|} \tag{9}$$

Where the "A" vector is the normal vector of the calibration plane, and the "B" vector is the difference between the camera focal point in 3D and the image center point's projection onto the calibration plane in 3D.

The projected camera distance along the calibration plane normal is the distance from the camera focal plane to the image center point's projection onto the calibration plane. This is the magnitude of the "B" vector (|B|) multiplied by the cosine of the perpendicularity angle. If preferred, equation 10 can be used instead of equation 9.

$$Distance\ C = Projection\ of\ B\ onto\ A = \frac{A \cdot B}{|A|} \tag{10}$$

The offset distance between the calibration and parallel planes containing the object must also be measured in the direction normal to both planes. The offset correction ratio ('R') is equal to the ratio of the calibration plane offset and the camera focal point's normal distance to the calibration plane, as shown in equation 11.

$$\textit{Correction Ratio}\ \text{"R"} = \frac{Offset\ Distance}{Distance\ C} \tag{11}$$

Finally, the corrected position ([DR'', CR'', UP'']) of any projected point into the correct parallel plane where the object actually exists is shown in equation 12.

$$\begin{bmatrix} DR'' \\ CR'' \\ UP'' \end{bmatrix} = \begin{bmatrix} DR' \\ CR' \\ UP' \end{bmatrix} + \boldsymbol{R} * \left(\begin{bmatrix} DR_{Cam\ FP} \\ CR_{Cam\ FP} \\ UP_{Cam\ FP} \end{bmatrix} - \begin{bmatrix} DR' \\ CR' \\ UP' \end{bmatrix} \right) \tag{12}$$

If the true focal point is too difficult or time consuming to determine, a reasonable approximation for the focal point is the center of a 300-mm camera lens, the most-commonly used lens at YPG. As wider FoV lenses are used, the focal length becomes smaller with the camera's focal point moving closer to the image sensor. It may be possible to set up the cameras reasonably perpendicular to the calibration plane or set up the reference points in a plane perpendicular to the camera's optical axis. The value of the offset correction ratio ("R") in this case is the ratio of the offset plane distance to the difference between the cross-range distance of the camera and the cross-range distance of the calibration plane.

INTERSECTION MEASUREMENT METHOD FOR THREE-DIMENSIONAL MEASUREMENTS

A better solution for correcting offsets is using two cameras with orthogonal views and then projecting the points into 3D space so that the points are not confined to a calibration plane. The camera views don't have to be perfectly orthogonal when using the calibration method proposed in the section, “Simple Matrix Algebra Method for Accurate Measurements,” but the geometric dilution of precision becomes worse when camera views are similar or 180 deg apart. Placing the two views as close to orthogonal (90 deg) as possible, but not closer than 45 deg or farther than 135 deg apart, is the recommended guidance.

With this approach, it is not necessary to ensure that the object being measured exists in the calibration plane, nor is it necessary for the calibration plane to be perpendicular to the camera view. Each camera must be calibrated as discussed in the previous section, “Simple Matrix Algebra Method for Accurate Measurements.” Then, identify the focal point as discussed in the previous section, “Correction for Measurements not in Calibration Plane.” If the cameras are perfectly synchronized, then a sharply identifiable object (such as a projectile's nose tip) must be selected in the matching frame from each video. The X and Y image coordinates from the camera view must be projected onto the calibration plane for each camera according to the method discussed in the previous section, “Simple Matrix Algebra Method for Accurate Measurements.” A 3D vector must then be computed for each camera. It should originate from the camera's focal point through the camera’s calibration plane projection point, as shown in figure 6.

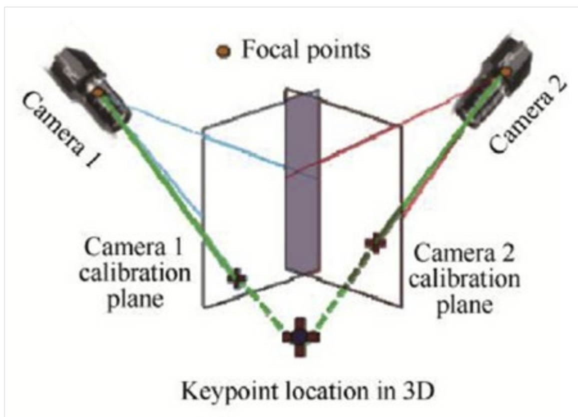

Figure 6
Intersection of two vectors in 3D (ref. 4)

For this process to work correctly, the point being projected must be identifiable in both image views clearly. Points such as a projectile's tip are usually visible from two orthogonal cameras, but other objects such as a fin on one side of a projectile may not be simultaneously viewable from the complementary camera. Computer vision analysis techniques (ref. 4) can aid in finding interior points in both views such as the center of gravity.

Due to small calibration errors, the two vectors from the different cameras are slightly askew and won't share an intersection point. The least-squares intersection point can be found using standard approaches in open literature (ref. 5) or several other open-source solutions can be used when conducting this analysis in MATLAB (ref. 6). Examining the least-squares error (which is computed in the same units as the 3D coordinate system) provides an indication about the accuracy of the measurements. A large error in the DR direction may indicate a time synchronization problem.

The time history of a video is often provided in Inter-Range Instrumentation Group (IRIG) or Global Positioning System (GPS) time (refs. 7 and 8), but the time history of a camera's video frames is not synchronized with the time history of another camera's video frames. It is usually easier to analyze several video frames and then fit a polynomial or spline-model to the X and Y pixel coordinates of a tracked object as it moves through the video frame. After the 2D motion fitted models are computed for both cameras, estimate the X and Y positions for any sample time occurring during the span of both videos. The estimated X and Y image positions at the selected sample time now can be projected onto the calibration planes. Then, use the procedure described earlier in this section to find the object's position in 3D at the selected sample time.

CONCLUSIONS

If a complete camera/lens system calibration is not possible, the simple field of view calibration procedure described in this report significantly reduces errors (by 20% or more with equipment of poor quality) from most photogrammetric analyses that do not account for lens aberrations and image skew. The process uses precision surveying, sub-pixel reference point selection, and also develops an affine transform based on the least-squares error of an overdetermined number of reference points. Computer vision algorithms work successfully with this method, especially when tracking the center of gravity or other critical geometric vertices of an object in three-dimensional space. Due to the simplicity of implementing this approach, it should be used when accurate measurements are required from video captured with fixed-view cameras during large-scale U.S. Army weapons testing.

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Edward Bauer

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